

THE EVOLUTION OF THE SONOBUOY FROM WORLD WAR II TO THE COLD WAR

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(Received November 5, 2013)

The primary airborne anti-submarine warfare sensor, the expendable sonobuoy, was developed during World War II in response to the devastating destruction of Allied shipping in the Atlantic caused by German U-boats. The simple radio-linked listening device thrown out of an aircraft in the 1940s proved revolutionary for air ASW. During the decades that followed, the evolution of the acoustic sonobuoy followed a number of directions. From the AN/CRT-1, the first passive omnidirectional broadband sonobuoy of World War II, to the AN/SSQ-53 DIFAR and AN/SSQ-77 VLAD, passive directional narrowband sonobuoys, and the AN/SSQ-62 DICASS, an active directional sonobuoy, of the Cold War, sonobuoys evolved in capability and tactical deployment in response to the increasingly sophisticated Soviet submarine threat. The development of the sonobuoy with its improving technology and in its multiple manifestations is described in counterpoint to the developing threat. The advance of operational concepts from CODAR to Julie and Jezebel to DIFAR are illustrated, and the influence of advances in underwater acoustics and the ocean environment upon sonobuoy design are discussed. The sonobuoy is shown to be a simple, reliable, inexpensive, technically complex, adaptive, and effective device that has been produced by the millions and used for almost seventy years.

I. INTRODUCTION

The sonobuoy is an expendable, air-deployed acoustic sensor to detect submarines. Invented during World War II as part of the U.S. response to the enemy submarine threat that was having a devastating effect on Allied shipping, it later became the primary air Antisubmarine Warfare (ASW) sensor of the Cold War and continues to be effective in conducting acoustic ASW. It provided the air platform with the capability of using underwater sound to determine if an enemy submarine is present.

In its simplest form, the sonobuoy is a compact, self-contained package of electronics designed to be dropped from an aircraft, enter the water, separate into an underwater acoustic sensor and an on-the-surface radio transmitter, and relay the underwater acoustic signals it detects to the aircraft, where the radio frequency (RF) transmission is received and processed to detect, locate, and track submarines at sea. The sonobuoy provides the underwater ears for the aircraft. Just as the submarine threat has changed over the decades, so has the sonobuoy, along with the ASW receivers, processors, aircraft, and concepts of operation. Technological advances in submarines and antisubmarine sensors have alternately spurred the other to further progress. New challenges were met with innovative responses, and the air ASW acoustic sensors transformed to meet each new situation.¹

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Report Documentation Page			Form Approved OMB No. 0704-0188		
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1. REPORT DATE APR 2012		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE The Evolution Of The Sonobuoy From World War Ii To The Cold War (U)				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Navmar Applied Sciences Corporation Warminster, PA 18974				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADC082812. U.S. Navy Journal of Underwater Acoustics. Volume 62, Issue 2, April 2012 - Airborne Anti-Submarine Warfare (ASW)					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 25	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

UNCLASSIFIED

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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II. BACKGROUND

The first serious threat from submarines came during World War I when Germany began attacking Allied shipping with U-boats. While the diesel powered U-boats were equipped with torpedoes, they were essentially surface vessels that could submerge for short periods of time and were forced to surface frequently to recharge their batteries. The U-boats would only submerge when they were going to attack or were under attack themselves. While on the surface, submarines were vulnerable to being observed and attacked from the air. The Germans used Zeppelins to patrol the North Sea and to attack British submarines, and when the German U-boats began the indiscriminant sinking of merchant vessels, Britain produced the Submarine Scout airship, the first aircraft intentionally built for ASW.²

After Wilbur and Orville Wright's first successful airplane flight in December 1903, the idea of the flying machine developed quickly. In late 1915, the British began flying seaplanes on patrol and introduced aerial ASW by attacking German submarines off the coast of Belgium with the recently devised depth charge. Hunting submarines by aircraft became a well-established practice. Eighty percent of aircraft submarine sightings were of surfaced U-boats, with the remaining twenty percent of vessels at periscope depth. While the aircraft could see the submarine from a range of 5 miles, observers on the submarines could spot the aircraft at twice that distance. U-boats needed 2 minutes to submerge, which was not enough time to avoid air attack. Later, improved U-boats could submerge in about a minute, making air ASW more difficult. The German submarine problem continued unabated until the convoy system, using escort ships and aircraft for protection, was introduced. Land-based aircraft, limited by range, assisted in locating U-boats and forced U-boats to submerge during daylight hours.^{2,3,4}

In 1915, the British began experiments with hydrophones to listen for submarine propeller noise, and in April 1916, the German U-boat UC-3 was the first submarine to be detected by a hydrophone and sunk as a result. In February 1917, the U.S. Naval Consulting Board, headed by Thomas Alva Edison, established a Special Problems Committee with a Subcommittee on Submarine Detection by Sound.

Some attempts were made to combine air ASW and underwater acoustics by using hydrophones suspended from seaplanes and flying boats. The hydrophones had to be lowered into the water while the airplane sat on the surface. Since the aircraft had to shut down its engines to use the hydrophone, there was reluctance to use this method for fear the aircraft engine would not start again. Blimps were found to be better platforms for hydrophones, but the war ended before they could begin widespread operation.²

Between the wars, research in underwater acoustics continued with the introduction of commercial fathometers to determine water depth in 1924 and quartz crystal transducers that led to the first experimental sets of echo-ranging apparatus to be installed on U.S. Naval vessels in 1928. In 1933, the Navy made 20 sets of echo-ranging SONAR (SOund NAvigation and Ranging) equipment.^{2,5,6,7} An early precursor to the sonobuoy that was proposed in 1931 by the U.S. Coast and Geodetic Survey (C&GS) was the "sono-radio buoy" to replace a ship as a Radio Acoustic Ranging (R.A.R) station. The sono-radio buoys that were placed in use in July 1936 were large, using barrels for flotation and to house electronics and batteries, as shown in Fig. 1. An electromagnetically activated hydrophone detected explosive detonations and relayed them by radio, using time delay methods to measure range.^{8,9}

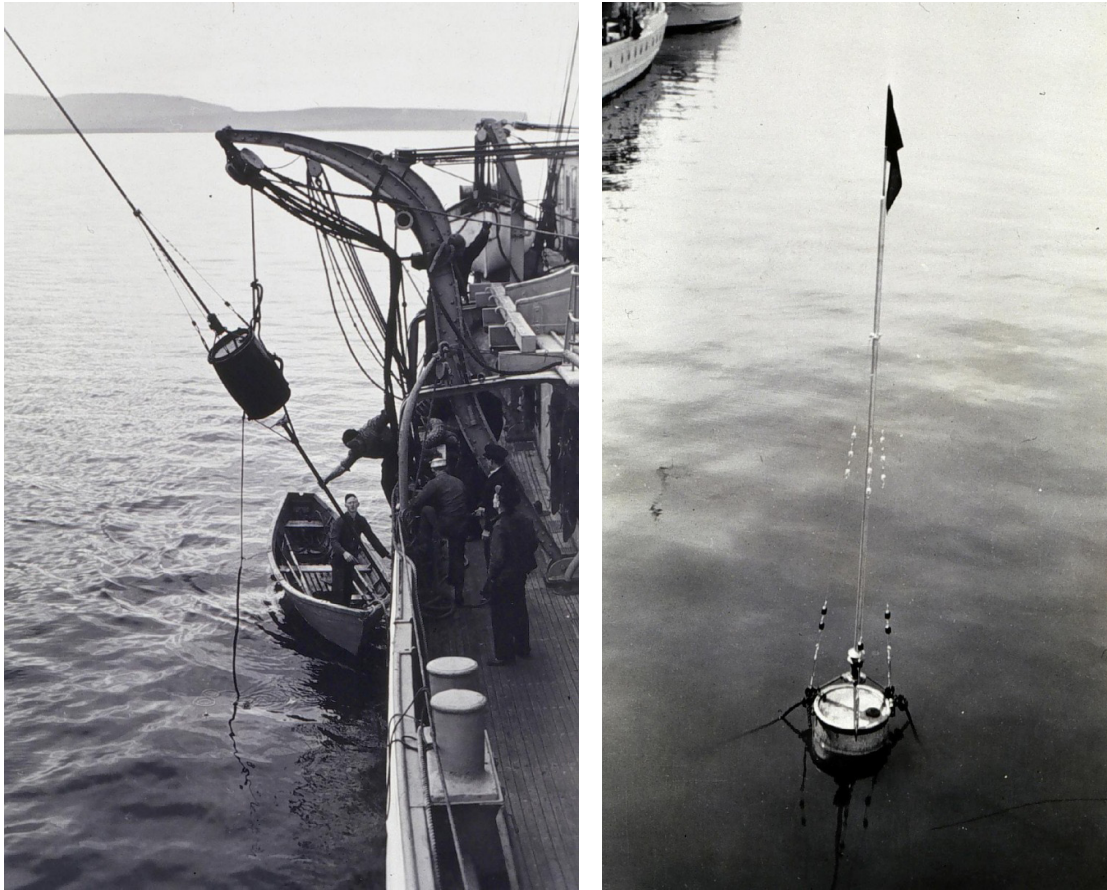


Fig. 1 – The Sono-radio-buoy used in C&GS Radio Acoustic Ranging Operations

III. THE EVOLUTION OF THE SONOBUOY

World War II

On 3 September 1939, England and France declared war on Germany, and the Battle of the Atlantic officially began. Based on their experience with submarine attacks in World War I, the British began using the convoy system to escort shipping, augmented by land-based aircraft of the RAF Coastal Command. Although they were limited in range and lacked the weaponry to deliver a decisive attack, the aircraft were effective in spotting and attacking U-boats, causing them to submerge, and preventing their attacks on shipping. In 1941, Germany began using wolf-packs for coordinated attacks on Allied ships by multiple U-boats, and in that year, sank 1,118 Allied ships. Ninety-five percent of the U-boats that were detected by the Allies escaped.^{4, 6} To combat U-boats that attacked shipping off the east coast of the United States, the Navy and Army Air Force flew antisubmarine patrols, attempting to spot the U-boats visually when they surfaced, but until March 1942, the aircraft had no radar and could not fly at night.¹⁰

In May 1941, P.M.S. Blackett, head of the British Admiralty committee for anti-submarine measures, proposed the idea of an expendable air-launched sonar system, or sonar buoy.¹¹⁻¹⁴ Washington replied it that had already begun a project that embodied some of the same problems without the use of an airplane.¹⁵ Vannevar Bush, an advisor to President Roosevelt, established the Columbia Underwater Sound Lab at Fort Trumbull, New London, Connecticut, and in June 1941, the Office of Scientific Research and Development (OSRD) awarded a contract to RCA, Camden, New Jersey, to develop a radio sonobuoy to be deployed from surface ships behind convoys to detect trailing U-boats.^{13, 16, 17}

RCA delivered the first models of its ship-deployable buoy in less than three months. These 60-pound sonobuoys were tested in September 1941, at Barnegat Bay, New Jersey. They worked well enough to prove the concept, even though the first models were noisy and leaked. The Navy decided to pursue higher priority efforts, and work on the sonobuoy was officially stopped.^{13, 17} In February 1942, the U.S. Navy's Coordinator of R&D requested the National Defense Research Council (NDRC) to develop an expendable radio sonobuoy for use by lighter-than-air craft, and development was begun at the Columbia Underwater Sound Lab.^{12, 16, 17}

Contrary to the official stop work order, the RCA buoys had been cleaned up, repaired, and put on the shelf. Within weeks of the Navy's request, the practicability of using a radio sonobuoy in aerial ASW was demonstrated on 7 March 1942, in an exercise conducted off New London with the S-20 submarine and the K-5 blimp, which monitored two refurbished RCA ship-launched sonobuoys. The buoys detected the sound of the submerged submarine's propellers at distances up to three miles, and the radio reception aboard the blimp was satisfactory up to five miles.^{11, 12, 13}

The first air-droppable sonobuoy weighed about 15 pounds and was packaged in a cylinder approximately 3 feet long and 5 inches in diameter. This size for sonobuoys later became standardized as A-size. Avoiding the use of materials that were critical in wartime, the outer cylinder for the first buoys was a quarter-inch thick paper tube coated with an alkyd resin to keep it watertight for a few hours. Wooden disks at the ends of the combined electronics and battery compartment were sealed by adhesive tape and flexible pitch, providing watertight integrity. A hole in the lower disk was sealed with a water soluble material that allowed the buoy to sink after a few hours' time.^{13, 17}

It had an FM reactance-modulated, one-half watt radio transmitter tuned to any one of 6 FM color-coded frequencies in the 60 to 72 Megahertz band and used five low-drain filament vacuum tubes with power provided by flashlight batteries. It had a steel monopole antenna and a nickel magnetostriction hydrophone suspended to a depth of 24 feet. The shallow depth resulted from hydrophone matching problems and the size of the electrical wire that connected it to the electronics.^{13, 17}

Originally intended to be dropped manually from blimps, the early developmental units were tested by dropping them off high bridges. When it was decided to drop them from airplanes, parachutes were added to the buoys, and the rigid antenna was replaced by a stored, self-erecting one. In June 1942, the first operational passive broadband AN/CRT-1 sonobuoy, shown in Fig. 2, was issued. The operational frequency of the AN/CRT-1 was 300 Hz to 8 kHz within the frequency range of the human ear and processing of the transmitted signal was aural. The operator had to make real-time decisions based on his ability to distinguish various underwater sounds. The AN/CRT-1A, an improved version, also known as the Expendable Radio SonoBuoy (ERSB), had an increased frequency band of 100 Hz to 10 kHz and lighter weight (12.7 pounds). The suspension cable was stored inside the hollow shell to reduce the buoy length by 4 inches (to 40 inches overall) from the earlier design.^{11, 17, 18, 19}

Upon launch, a static line attached to the airplane tore off the parachute cover to allow the orange 24-inch diameter parachute to open. The antenna telescoped and protruded through a hole in the parachute. The antenna was a 39-inch quarter-wave steel tube, with about 9.5 inches of the antenna insulated from the water by a watertight sleeve. One of the parachute shrouds pulled a switch pin to turn on the transmitter. In the water, the parachute remained attached and settled around the antenna base.²⁰

The amplifier and RF transmitter inside the sealed upper compartment were mounted on either side of a rectangular plate with the audio amplifier on one side and the RF circuit on the other. The plate was mounted on four shockproof rubber supports to isolate the circuitry from microphonic noise, and each vacuum tube socket had its own rubber mounting. The FM transmitter provided an effective RF antenna radiation of 0.1 watt. It was powered by four parallel 1.5-volt flashlight cells for filament voltage and two series 67.5-volt miniature batteries for plate voltage, providing 4 hours continuous operation.²⁰

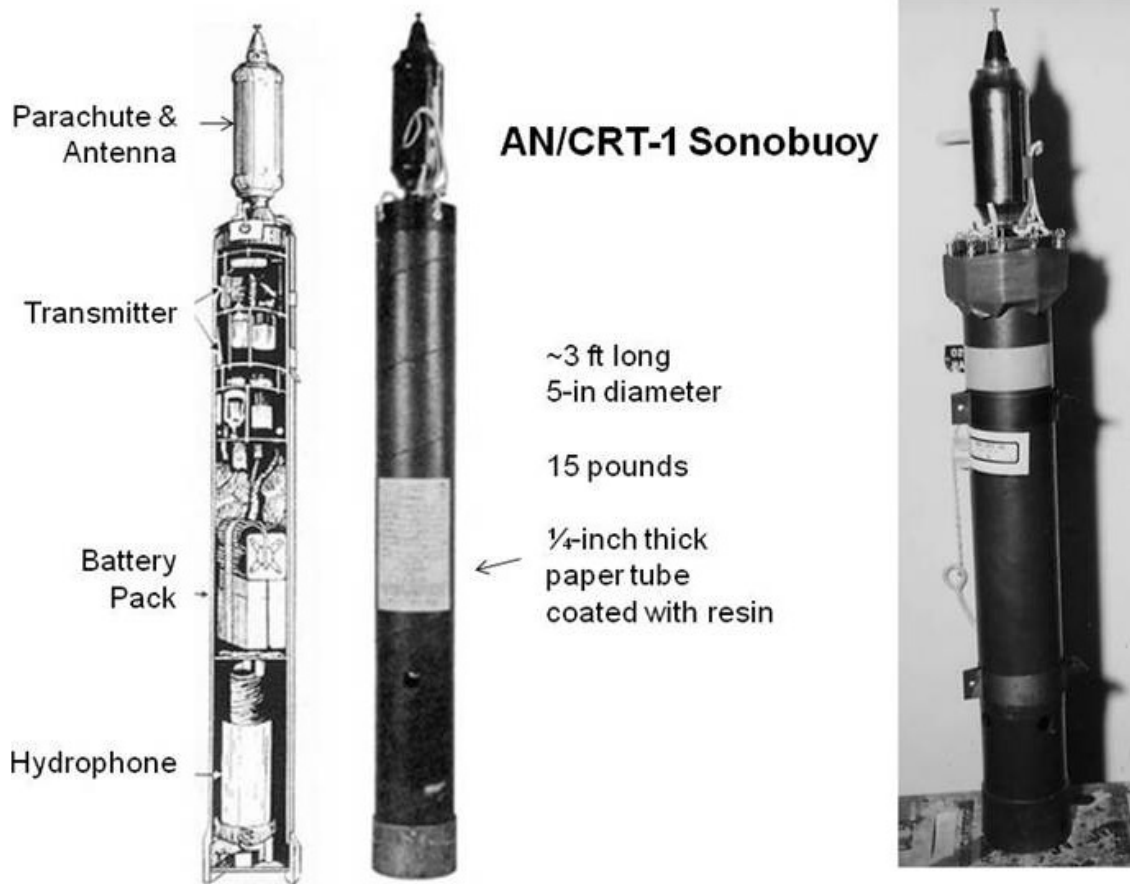


Fig. 2 – The AN/CRT-1 Sonobuoy

On 15 October 1942, the Army Air Forces Antisubmarine Command (AAFAC) was activated to locate and destroy hostile submarines and to assist the Navy in the protection of friendly shipping. The key to the AAFAC offensive was the U-boat's need for frequent surfacing to recharge batteries and ventilate the boat. The U-boat would pursue merchant vessels on the surface, where it could travel much faster than when submerged. The U-boat would submerge only to avoid attack after firing its torpedoes. The air patrols would force the U-boats to dive and remain submerged until it was too late to catch up with the convoys.²¹

On 25 July 1942, the first successful launch of a sonobuoy from an aircraft was made from a U.S. Army B-18 bomber.^{12, 17} By the end of October, the procurement of the expendable radio sonobuoy had been initiated when the Bureau of Ships ordered 1,000 sonobuoys and 100 associated receivers. Subsequently, the Army Air Corps ordered 6,410 of the AN/CRT-1 sonobuoys, while the Navy ordered 1,800 units.^{3, 13, 17} By 1943, RCA had begun full-scale sonobuoy production.

The anti-submarine "Hunter-Killer" groups were established by the U.S. Navy to provide convoy protection and to pursue and sink enemy submarines. On 5 March 1943, the U.S.S. Bogue (CVE-9) was the first of 17 escort carriers to begin a systematic ASW campaign as the center of a hunter-killer group assigned to escort trans-Atlantic convoys to Europe. These carriers were capable of ranges of over 26,000 miles at 15 knots. At 492 feet in length, the escort carriers of the Bogue class could operate up to 28 sonobuoy and antisubmarine weapon-equipped aircraft, including Wildcats (Grumman F4Fs or GM FM-1s or FM-2s) and Avengers (Grumman TBFs or GM TBMs), with greater reliance on the Avengers.^{22, 23, 24}

The German Admiral Doenitz required U-boats to radio back to headquarters. These high frequency (HF) transmissions were intercepted by the Allies using Direction Finding (DF) techniques. Using HF/DF (or “Huff Duff”), visual contacts, and sonar, the Hunter-Killer Group would pursue the U-boat until they lost or destroyed it. Sometimes, they were cued to the position of a U-boat by the interception of coded message traffic from the U-boat thanks to the British capture of a U-boat with the Enigma coding machine used for submarine operations. By December 1942, the Allies had cracked the codes and were able to decipher intercepted messages to and from the U-boats. The code name Ultra was used to describe the Allied capability to decipher German messages.^{10, 25, 26, 27}

In February 1943, the design for the AN/CRT-4, a directional sonobuoy was begun. It was a broadband passive buoy with a rotating directional hydrophone. Larger and heavier than the AN/CRT-1, it measured 6.25 inches in diameter and 52.5 inches in length and weighed 30 pounds. The directional hydrophone was turned at a rate of 3 to 5 times a minute by a gravity motor using a 500-foot long fish line. Testing took place in early 1945, too late to affect the war, and it was not pursued further.^{11, 13, 17, 28}

In 1943, Germany developed the snorkel, allowing U-boats to expel diesel exhaust and draw in fresh air while the submarine was at periscope depth and less detectable by radar.⁶ When the AAFAC was disbanded in August 1943, many of the ASW B-24 Liberators were turned over to the Navy and redesignated PB4Y-1s for the ASW mission. In December 1943, sonobuoys were assigned to ASW squadrons, and by 1944, the Navy had ordered 59,700 AN/CRT-1A sonobuoys. These sonobuoys were manufactured with six RF channels. Each channel corresponded to a color (purple, orange, blue, red, yellow, and green) and was received on the AN/ARR-3 receiver, which the operator manually tuned (Fig. 3) in one buoy at a time using the color-coded tuning window to compare the intensity of the sound. Automatic Frequency Control (AFC) allowed rapid tuning for comparative listening.^{13, 29, 30, 31}

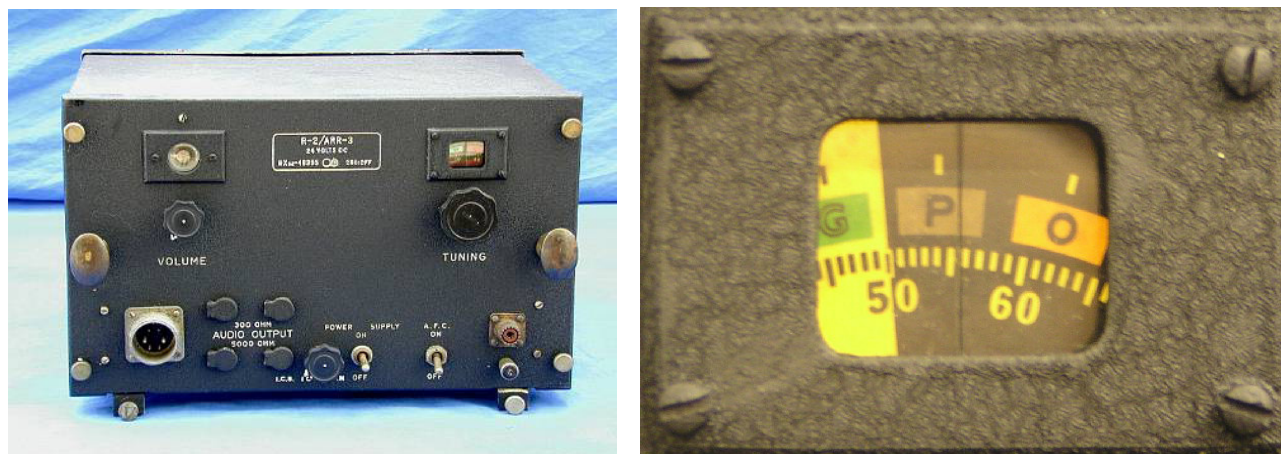


Fig. 3 – R-2/ARR-3 Aircraft Receiver for Sonobuoys and Color-coded Tuning Window

Typically, the aircraft would drop a purple sonobuoy on the suspected position of a submarine and follow with four other color buoys, deployed as the aircraft flew in a cloverleaf pattern (Fig. 4). By over-flying the purple buoy on each leg of its run, the aircraft could position the other buoys, one per pass, at a distance of 2 miles from it. The usual order was Purple, Orange, Blue, Red, and Yellow (POBRY), with Green being reserved as a backup. The whole maneuver took about 13 minutes. When an aircraft had a contact on a surfaced submarine, it would approach at 300 feet, dropping a torpedo and one or more buoys to listen for the explosion or the cavitation of the submerged submarine’s propellers. If the kill was not confirmed, additional buoys would be dropped to relocate and track the target, as shown in Fig. 5. Sonobuoys were launched from the bomb bay or by hand.^{2, 3, 17}

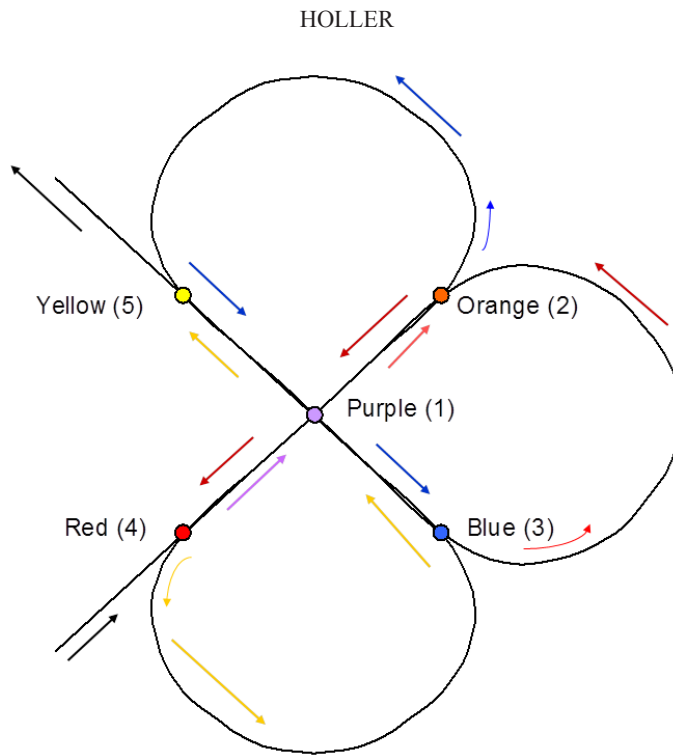


Fig. 4 – POBRY Sonobuoy Deployment Pattern (after Price)

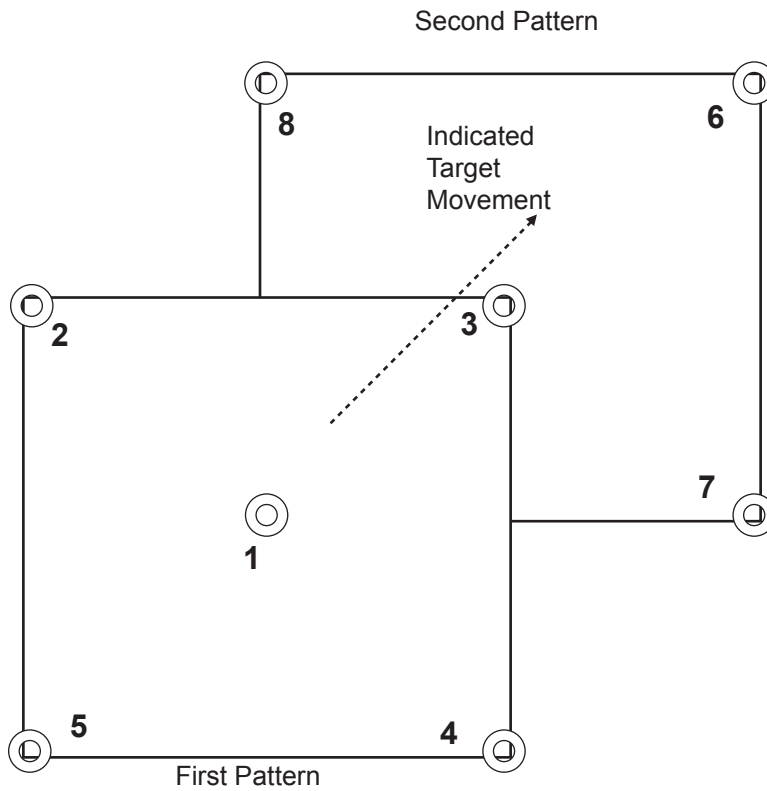


Fig. 5 – Sonobuoy Search Pattern Followed by a Tracking Pattern

Some sonobuoys were equipped with one-pound packs of fluorescent dye to make them visible in daylight and/or a strap-on collar with a night-light for nighttime use. Although they normally had a four-hour battery life, some buoys were modified by strapping on a separate container with extra batteries, as shown in Fig. 6, in order to use the sonobuoys in long-life barriers. The sonobuoys used simple dry cell batteries that had poor shelf life. The batteries were replaceable in the field with the intent that they would have fresh batteries when they were used. However, the oldest batteries in storage were often issued first to get rid of them. Even with this handling in the field and the use of unreliable batteries, the sonobuoys that were properly-serviced in good squadrons achieved around seventy percent reliability.¹³

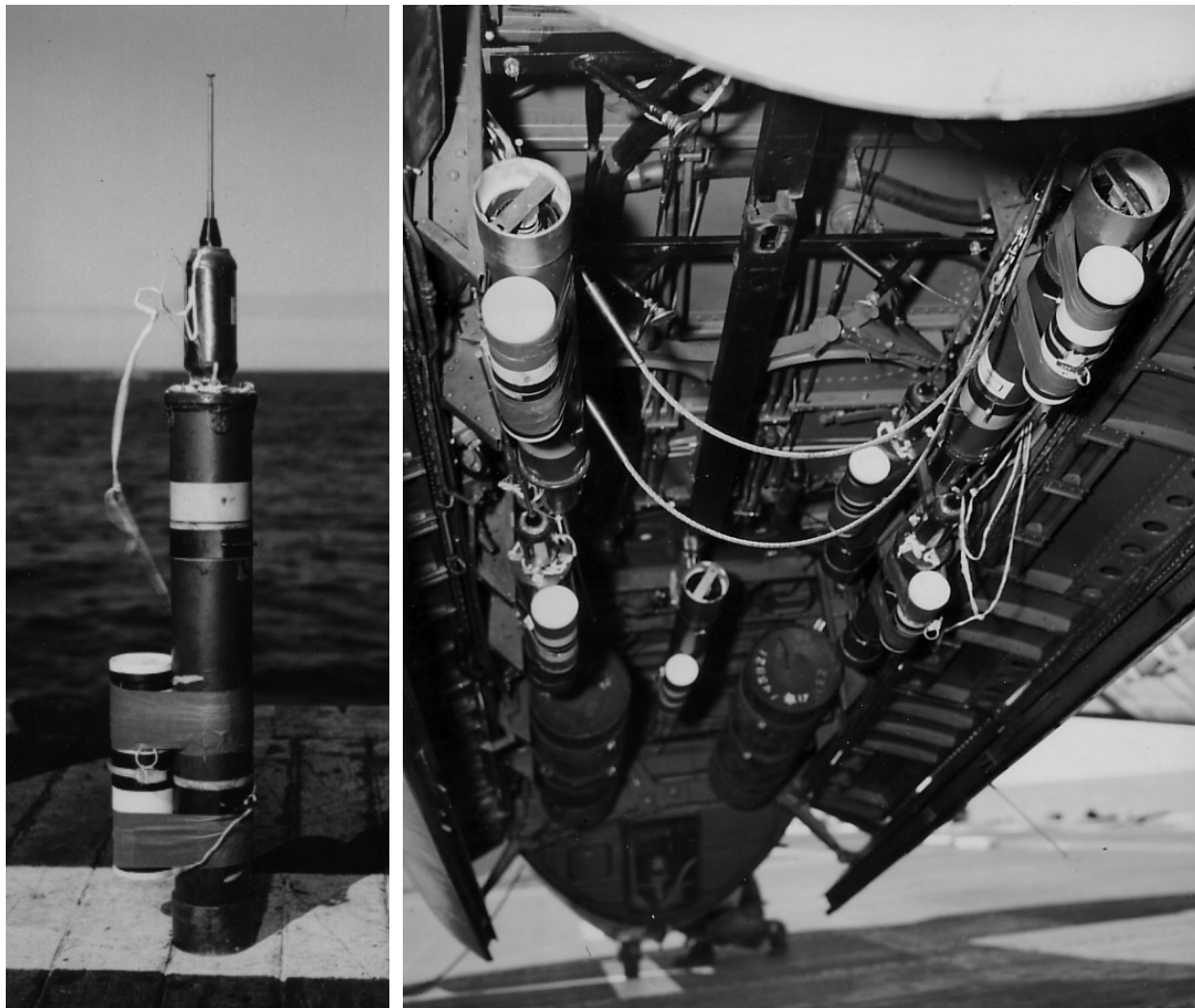


Fig. 6 – AN/CRT-1A Sonobuoys with Extra Battery Containers

In June 1944, the *USS Bogue* used sonobuoys to score a kill against a Japanese submarine in the Atlantic. The IJMS submarine I-52, a Japanese Type C-3 cargo submarine, departed Kure, Japan, on 10 March 1944, for Germany for the exchange of strategic materials and goods in accordance with the Axis Tripartite agreement. The I-52 rounded the Cape of Good Hope and was in touch with both Tokyo and Berlin by radio. The Allied Ultra intercepts of the I-52's transmissions let them track the submarine, and the *Bogue* was instructed to hunt it down.^{32, 33}

On 22 June, the I-52 rendezvoused with the German U-boat U-530 in the Atlantic about 850 miles west of the Cape Verde Islands. The U-530 departed for Trinidad in time to avoid the Grumman TBF Avenger from the Bogue that arrived overhead at 2,340 hours on 23 June, while the I-52 was running on the surface at night in bad weather. The Avenger first dropped a flare to illuminate the Japanese submarine and followed it up with two 354-pound Mark-54 depth bombs. The I-52 crash dived to evade the attack, and the Avenger dropped a purple-coded sonobuoy, followed by orange, blue, red, and yellow buoys. By listening to each sonobuoy in succession, the position of the submarine was determined by the relative intensity of the sound emitted by the target. Following detections by the sonobuoys, the Avenger released a Mark-24 "Fido" acoustic homing torpedo. Other Avengers from the Bogue picked up propeller sounds on the sonobuoys, and a second torpedo was launched, followed by a loud explosion. The sonobuoys picked up no further sounds from the submarine, and in the morning one of the Bogue's escorts, discovered the I-52's flotsam of raw rubber, silk, and human remains.^{31, 32, 34, 35}

On 20 August 1944, the Bogue came across U-boat U-1229 about 300 miles southeast of Cape Race, Newfoundland, en route to put a German spy ashore on the coast of Maine. An Avenger from the Bogue attacked the U-boat with MK-5 rockets and two MK-54 depth bombs. The damaged U-boat submerged. The Avenger dropped a purple sonobuoy within 15 seconds of the submergence. For almost a minute, the sound of a propeller was heard on the sonobuoy, but this was followed by hammering sounds, then silence. An oil slick was observed. A standard pattern of four additional sonobuoys, blue, red, yellow, and green, was dropped around the purple one as a center. There was no indication of sound from the submarine, but other aircraft were sent to follow up. One aircraft, informed that only two of the sonobuoys were operating, dropped four more buoys. The U-boat resurfaced, was attacked by two Avengers with depth bombs and rockets, and sank, leaving 42 survivors in the water.^{26, 27}

In 1945, the Allies won victory in Europe and the Pacific. While just over 150 enemy U-boats were destroyed from 1939 to 1942, the Allies destroyed nearly 600 U-boats from 1943 to 1945, when Hunter-Killer groups were operating with air ASW.^{34, 35} Forty percent of enemy submarines destroyed during the war were by aircraft or aircraft in conjunction with ships. Once a U-boat was located, sonobuoys were instrumental in determining where it went after submerging and how successful the subsequent attack was. An indicator of the value of the sonobuoy in the war is that, from October 1942 to the war's end in 1945, the U.S. Navy had ordered 150,000 sonobuoys and 7,500 sonobuoy receivers.¹³

The Start of the Cold War

At the end of World War II, the OSRD laboratories were dismantled, and NRL absorbed the New London Laboratory, terminating research and development on sonobuoys on the assumption that sonobuoys would not be needed in the post-war era. Airborne ASW went without any coordinated technical guidance until nearly 1950 when the Naval Air Development Center (NADC) in Warminster, Pennsylvania, began to spearhead the development of sonobuoys.¹⁷

After World War II, the Allies sank or destroyed most of the remaining German U-boats, but some were divided among the victors. The Soviet Union received 10 of the German U-boats, including 4 of the most advanced Type XXI submarines. By January 1948, the Soviets had produced their own submarine and had 15 Type XXIs in their fleet.^{36, 37} From June 1948 to May 1949, the Soviet Union's blockade of Berlin triggered the Berlin airlift and inflamed Western fears of the USSR. The outbreak of the Korean War in 1950 marked the true beginning of the U.S.-Soviet Cold War.³

In 1950, spurred by the possibility of a Soviet submarine threat in the Atlantic that would soon surpass that of the World War II German U-boats, Bell Labs initiated a crash program for the Office of Naval Research to develop SOSUS (SOund SURveillance System), a network of deep ocean long range acoustic sensor arrays to locate, classify, and track Soviet submarines. The SOSUS concept was based on the deep sound channel, or SOFAR (SOund Fixing And Ranging) channel. The low frequency acoustic R&D effort, called Project Jezebel, combined the Bell Labs LOFAR (LOW Frequency Analysis and Recording) equipment with a prototype hydrophone array installed by Western Electric. The SOSUS ocean surveillance program expanded to cover large areas of the Atlantic and Pacific Oceans.^{3, 5, 38-41}

The Soviet submarine fleet grew in the 1950s with Zulu and Whiskey type submarines that were based largely on the German type XXI U-boats, and the U.S. Navy renewed its interest in air ASW and sonobuoys. The AN/CRT-4 directional sonobuoy was restarted as the AN/SSQ-1. The omnidirectional broadband passive successor to the AN/CRT-1A was the A-size AN/SSQ-2. The two buoys were intended to be used sequentially, with the lower cost omnidirectional sonobuoy doing the initial detection and the more expensive directional buoy obtaining a cross-fixed localization.^{3,4,13,42} The first acceptable AN/SSQ-2 (XN-2) sonobuoy was delivered in 1951, and the AN/SSQ-2B became the first mass-produced sonobuoy. It had reliability problems largely attributable to the need for Fleet personnel to partially disassemble the buoy, insert batteries, reassemble the buoy, and peak and tweak it before use.

The AN/SSQ-1 directional sonobuoy experienced delays in its development until 1954, when Magnavox began working on the design of a one-hour-life sonobuoy with a 50-foot deep mechanically rotated hydrophone to provide passive bearings listening in the 15 kHz to 17 kHz acoustic band. It weighed 60 pounds and was packaged in a cylindrical configuration called B-size (6.875-inch diameter by 60 inches long). Because the AN/SSQ-1, shown in Fig. 7 with the rotating directional hydrophone, was plagued with continuing problems, the U.S. Navy purchased, in the interim, the AN/SSQ-20, an Americanized version of the British T-1946 directional sonobuoy.¹³ The land-based SOSUS system was highly effective at long ranges and was able to provide bearings from different stations to establish contact areas for Soviet submarines. With the fixed sonar systems as main sensor for submarine surveillance, the VP aircraft became the means of rapidly prosecuting the SOSUS detections, and aircraft-deployed sonobuoys became the principal sensors for tactical search and localization of submarines.

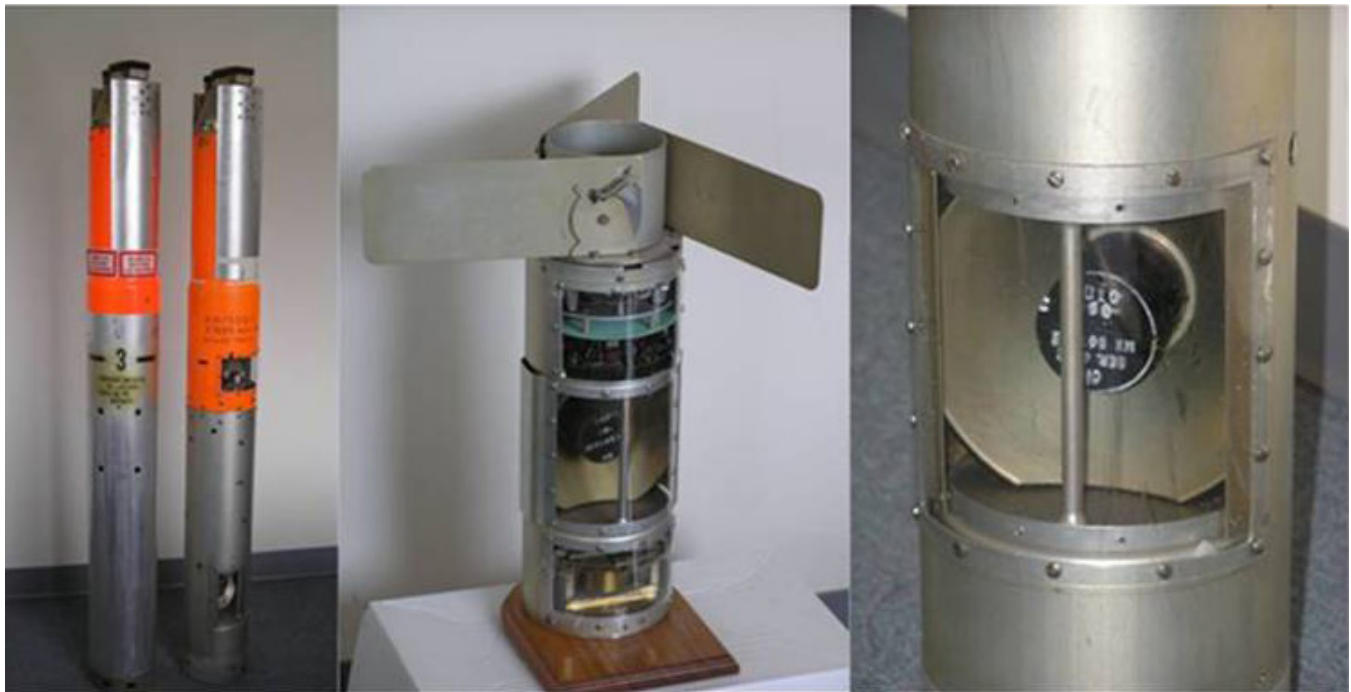


Fig. 7 – AN/SSQ-1 and 1A Sonobuoys Showing the Rotating Directional Hydrophone

In 1954, the Bureau of Aeronautics contracted Bell Telephone Laboratories (BTL) to determine the parameters for airborne LOFAR equipment and to develop a usable airborne localization technique. Two possible systems were investigated. One was to develop a directional hydrophone that could be steered electrically rather than rotated mechanically, and the other was to develop a technique of correlating the signals from two separated omnidirectional hydrophones. BTL built special directional sonobuoys with two orthogonal pressure-gradient hydrophones in a single case. Orientation of the hydrophones to the Earth's magnetic field was provided by attaching a strong Alnico bar magnet. This directional sonobuoy had serious self-noise problems below 50 Hz, and the bar magnets used in the buoys to align the hydrophones were so powerful that the MAD (Magnetic Anomaly Detector) system in the aircraft could not be used until all the directional buoys aboard had been dropped. As a result of these problems, emphasis was shifted to the omnidirectional sonobuoy correlation concept.

Improvements to the AN/SSQ-2B sonobuoy were initiated by BTL and developed by Magnavox. Designated the AN/SSQ-2 (XN-8), the sonobuoy was delivered in 1956. The improvements included: a miniature preamplifier in the hydrophone to reduce noise in the long cable, a compliant mass-terminated suspension to reduce hydrophone motion induced by surface waves, separation between the mass termination and hydrophone to prevent cable strumming being transmitted to the hydrophone, a one-watt RF transmitter with 16 fixed frequency channels, hydrophone depth of 80 feet, a 3-hour life provided by a silver-chloride seawater-activated battery, and a rotochute instead of a parachute for in-air retardation.

In 1956, LOFAR was first introduced in the VP community, and the AN/SSQ-28 passive omnidirectional Jezebel-LOFAR sonobuoy, the successor to the AN/SSQ-2 (XN-8), began production in 1960. The AN/SSQ-28 represented an important breakthrough in reliability with the introduction of factory-installed water-activated batteries. The AN/SSQ-28 was the first true LOFAR sonobuoy, operating at frequencies between 10 and 2500 hertz, giving the air ASW the capability of exploiting the low frequency regime used successfully by SOSUS. The AN/SSQ-28 was an A-size sonobuoy weighing 18 to 20 pounds with a piezoelectric ceramic hydrophone at a depth of 95 feet. It was the first sonobuoy to use a quartz-stabilized transmitter and had sixteen fixed frequency RF channels. It had a suspension cable with silicone rubber insulated multi-strand conductors wound helically inside a silicone rubber cable, allowing the cable to stretch elastically to reduce the motion of the hydrophone. It also had a half-wavelength coaxial aluminum rod antenna extended above the water surface to prevent washover.⁴³

The omnidirectional sonobuoy could sense a submarine within range of its acoustic detection capability with no indication of the target's range or bearing. The correlation concept pursued by BTL used a pair of sonobuoys with known spacing between them. Using broadband signals from the two buoys, a time delay was introduced between the two signals until they matched for maximum cross-correlation. From the time delay introduced, the bearing could be determined. The signals from the two buoys were multiplied in a correlation circuit and were plotted on a display of bearing versus time. This was called CODAR (CORrelation Detection And Ranging). Two pairs of buoys were needed to resolve directional ambiguity and provide a cross fix, as in Fig. 8. For the use of LOFAR for detection and classification and CODAR for localization, a LOFAR-CODAR recorder was developed for the aircraft. While the correlation technique worked, the time required to place the four buoys often exceeded the time that the submarine was snorkeling, and CODAR did not work well when the submarine went quiet.^{3, 13, 28}

When a sonobuoy was used strictly as a passive narrowband device, it was said to be employed as a Jezebel buoy, after the project that developed SOSUS. The buoy could also be used in another mode. A small explosion from a practice depth charge could be set off near the sonobuoy, creating a broadband high energy pulse, and the sonobuoy would act as the receiver for the echo from the submarine. This mode became known as "Julie" in 1955, when engineers who worked on the explosive echo-ranging concept saw a burlesque dancer named Julie Gibson at a Philadelphia nightclub and noted that her performance could turn passive buoys active. Julie was introduced into the Fleet in 1956, and the P2V aircraft was equipped with special Julie amplifiers built to drive the RD-47 MAD dual track pen recorder. Figure 9 illustrates Jezebel and Julie.^{13, 28, 42}

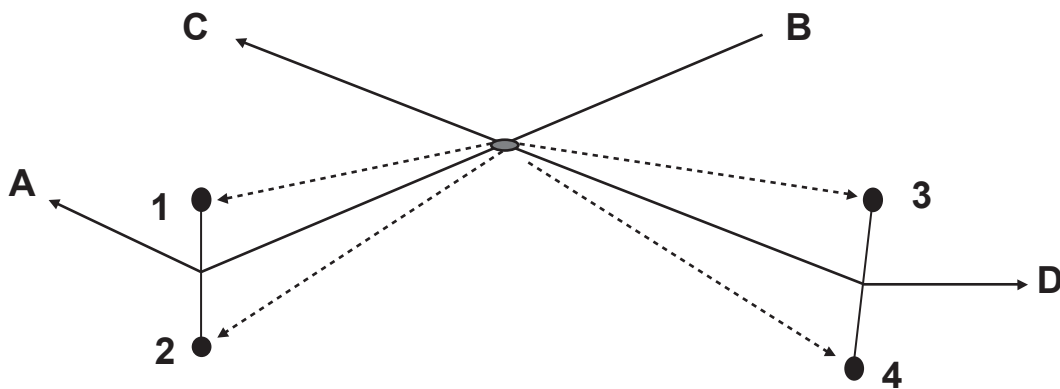


Fig. 8 – CODAR Target Location from Two Pairs of Sonobuoys

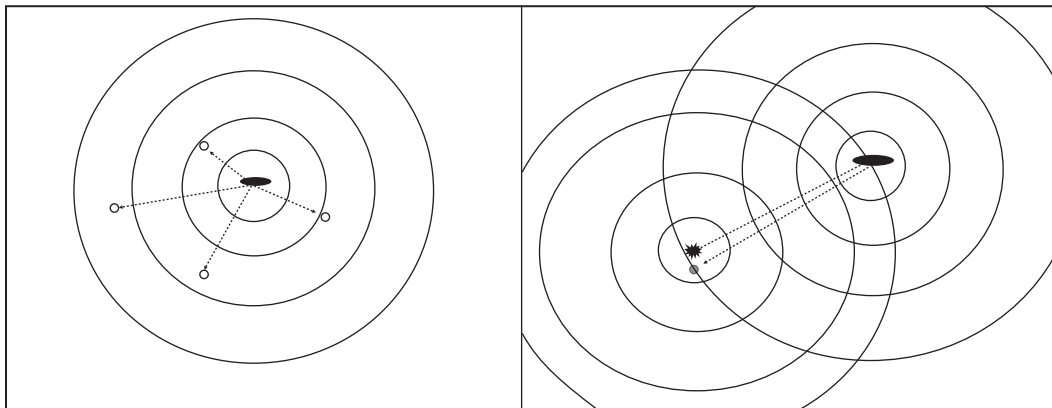


Fig. 9 – In Jezebel (Left), Sonobuoys Listened Passively for Radiated Sound from the Submarine; in Julie (Right), Sonobuoys Listened for an Echo off the Submarine from an Explosive Source

In 1957, the Soviets produced their first nuclear powered November class submarine. Similar designs were used in the Hotel class SSBNs (Nuclear-powered Ballistic Missile Submarines) and the Echo Class SSGNs (Nuclear-powered Guided Missile Submarines) built between 1958 and 1968. Each of these so-called HENs (Hotel-Echo-November) had two nuclear reactors, a double hull, and two fast-turning screws. Besides producing high acoustic levels of flow noise and cavitation, the HENs generated distinctive acoustic signatures based on characteristic tonals (discrete frequency acoustic emissions) arising from their propulsion turbines, their propeller rates, and the ratio of the tonals.^{3,44}

In 1957, the AN/SSQ-23 omnidirectional passive sonobuoy, the first low frequency modern sonobuoy, was deployed and used for Julie. It was a narrowband sonobuoy with a 60-foot deep hydrophone, operating in the 100 to 3000 hertz frequency range. Improvements to the Julie system were made by introducing an AN/ASA-20 Chart Analyzer/Recorder as part of the Julie/Jezebel ASW update to the P2V.⁴³ The high energy levels of the explosive sources in Julie caused considerable reverberation, and AGC (Automatic Gain Control) was added to the AN/SSQ-23 sonobuoy.¹³ Julie tactics required improvement in aircraft navigation and in sonobuoy location capability. The P2V-7 Julie/Jezebel configured aircraft had a Dead Reckoning Tracker (DRT) combined with the ASA-13 Navigation Computer and a pair of overhead circle projectors added. Smoke markers were dropped to evaluate wind drift, and the ARA-25 Radio Direction Finder was modified to operate in the sonobuoy frequency band to provide an On-Top Position Indicator (OTPI) for sonobuoy location.

In the 1960s, affordable active sonobuoys with a single-frequency coherent source were developed to provide Doppler recognition to separate moving targets from stationary objects. This, along with Julie's need for complex aircraft patterns, highly skilled operators, heavy data processing workloads, and air crew explosive-handling safety problems, led to the cancellation of Julie. The first production active buoy, the AN/SSQ-15, a range-only B-size sonobuoy, shown in Fig. 10 next to an A-size buoy, produced an omnidirectional continuous wave (CW) signal in the 26 kHz to 38 kHz frequency range. The same buoy received the echo return. Introduced in 1961, the AN/SSQ-15 was unpopular at first because of its unwieldy size and weight. Later, when Julie and CODAR were found to have detection problems, the AN/SSQ-15 with its reliable 2,500-yard range and Doppler capability found more acceptance.^{13, 28}



Fig. 10 – B-size AN/SSQ-15 Sonobuoys next to an A-size Buoy

The Distant Early Warning (DEW) Line across Alaska and Canada had been completed in 1957 because of concern of possible attack by long range Soviet bombers. This was extended across Greenland by 1961, and the Navy began barrier patrols with WV-2 (Willie Victor) aircraft out of Keflavik, Iceland, over the Greenland-Iceland-United Kingdom (GIUK) Gap. In the late 1960s, Soviet Yankee-class SSBNs began routine patrol sequences through the GIUK gap into the western Atlantic. Beginning in 1963, the WV-2s were given ASW capability, being modified with a sonobuoy launcher and receiver.^{45, 46}

In 1961, the Lockheed P-3 Orion, designed specifically to meet the submarine threat, replaced the P-2 Neptune. Originally designated the P3V-1, it became the P-3A in November 1962, when the Navy revised all aircraft designations. In 1964, the P-3 was improved as the P-3B, and in 1968, the P-3C was introduced. With an endurance of 12 hours, the P-3 is able to perform a 4-hour mission at a range of 1,000 miles and return to base. The P-3 is capable of carrying 84 sonobuoys, 48 in the external launch tubes in its fuselage and 36 internally. The sonobuoys are monitored from sensor stations within the aircraft.

In 1962, the Soviets produced the Juliett class of diesel electric SSGs (Guided Missile Submarines) with anechoic rubber tiles on the hull and announced that their nuclear submarines had fired ballistic missiles from submerged positions.^{4, 44} The Soviet Union deployed its first Hotel-class SSBN on a 70-day patrol into the North American Basin in April 1962.⁴⁵ By October 1962, the Cold War reached crisis stage when surveillance flights showed evidence of nuclear missile installations and Soviet missiles on Cuba. President John Kennedy presented the case to the United Nations and ordered a quarantine to blockade arms shipments into Cuba, stopping and inspecting all approaching ships, and communicated to Soviet leader Nikita Khrushchev that the missiles and installations had to be removed.^{46, 47, 48}

The Soviets deployed four Foxtrot diesel-electric attack submarines from the Kola Peninsula to the Caribbean Sea. To avoid ASW aircraft, they were sometimes forced to dive to 200 meters depth. After SOSUS contacts on the Soviet subs were made in the GIUK Gap, no tracks could be established by U.S. ASW forces. All 4 Foxtrots were eventually detected while snorkeling (3 by VP/VS aircraft). Successful Hunter-Killer and VP hold-down tactics forced them to surface for battery recharging. LOFAR, Jezebel, and Julie sonobuoys, as well as MAD, were used in the detection and tracking of the Soviet submarines, and all of them returned to base without making it to Cuba. U.S. ASW forces had processed submarine contacts for a total of 2,889 hours over a 23-day period. The crisis was resolved when the Soviets dismantled the installations and removed the missiles from Cuba.^{48, 49, 50, 51}

In 1965, the A-size AN/SSQ-41, an improved passive, omnidirectional LOFAR (10-6000 hertz) sonobuoy replaced both the AN/SSQ-23 Julie sonobuoy and the AN/SSQ-28 Jezebel sonobuoy to become the primary passive sonobuoy in the Fleet. The AN/SSQ-41 had a 4-element shaded line array placed at a depth of either 60 or 300 feet. The array provided some discrimination against surface and bottom reverberation in Julie operations. It had 31 fixed RF channels and a quarter-wavelength antenna.⁵² The AN/SSQ-48, a Jezebel buoy with a 95-foot-deep hydrophone was also developed in the early 1960s as a successor to the AN/SSQ-28, but it was replaced by the AN/SSQ-41B which had a single hydrophone. At this point, most operations were passive, and the hydrophone array was no longer serving any practical purpose. AN/SSQ-41B sonobuoys operated in the 10 to 10,000 or 10 to 20,000 hertz band.⁵³

The AN/SSQ-57 calibrated LOFAR sonobuoy was introduced in the early 1970s. These sonobuoys were individually calibrated by the manufacturer for precision acoustic measurements, since they were used to measure ambient noise in the ocean. To provide a wider range of dynamic range in noisy environments, a selectable 20 dB attenuation pad was incorporated into the 10 to 10,000 Hz sonobuoys. The AN/SSQ-57A extended the acoustic frequency band from 10 to 20,000 Hz. The maximum launch altitude was increased to 25,000 feet, and the maximum launch speed was increased to 380 knots, requiring the replacement of the rotochute with a parachute, initiated by a wind flap. The buoy canister surface float was replaced with a CO₂ inflated urethane-impregnated bag surface float.^{54, 55, 56}

With the introduction of LOFAR and a frequency response down to 10 hertz, sonobuoy self-noise from mechanical and hydromechanical sources, was a problem. An isolation mass and an elastic suspension cable reduced this noise. The sonobuoys of the mid-1940s were reconfigured by the early 1960s into far more sophisticated devices for submarine detection, as illustrated in Fig. 11.

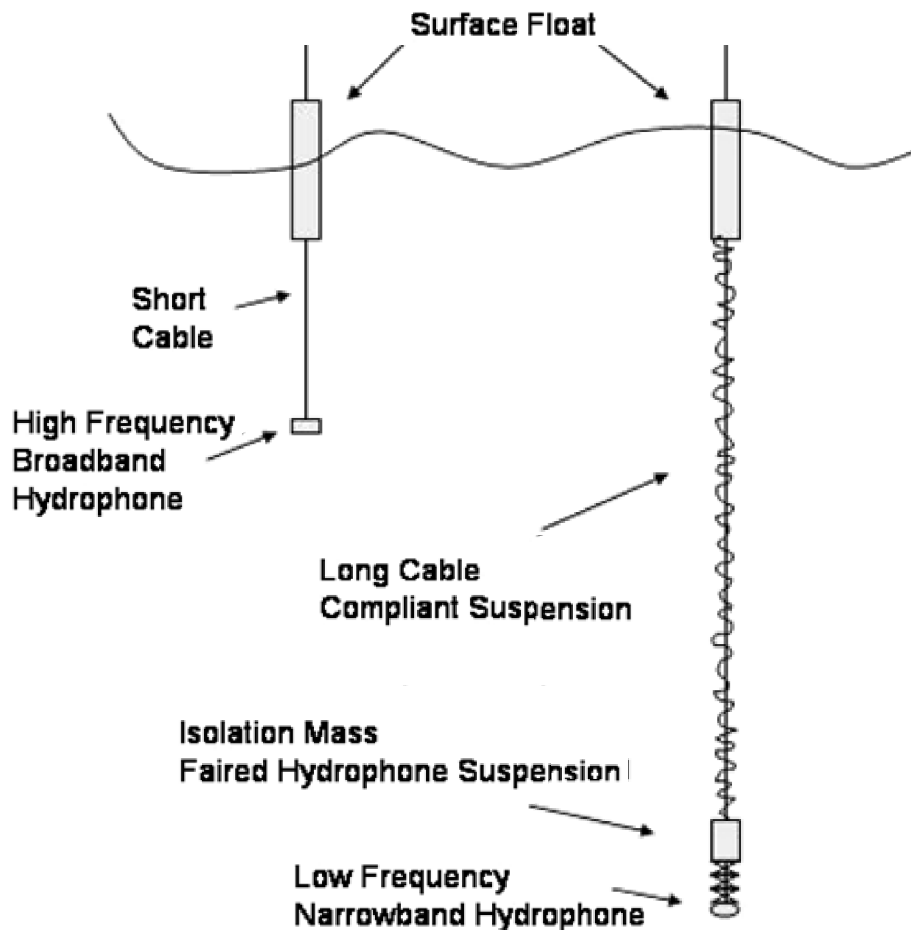


Fig. 11 – The Changes between Sonobuoys of the Mid-1940s and the Early-1960s

The Directional Sonobuoy

In 1965, development of the AN/SSQ-53 DIFAR (DIrectional Frequency Analysis and Recording) passive directional sonobuoy was begun. The directionality of the sensor was obtained by employing two orthogonal horizontally oriented directional sensors, a compass element, and an omnidirectional pressure hydrophone to provide a resultant unambiguous bearing to the target. The DIFAR concept multiplexed the compass information and the data from the two directional hydrophones and the omni hydrophone using a 7.5 kHz frequency reference pilot tone and a 15 kHz phase pilot tone, which was phase shifted to reference magnetic North and provided the carrier frequency for the amplitude modulated directional data in its sidebands, shown in Figs. 12. and 13.^{57, 58, 59}

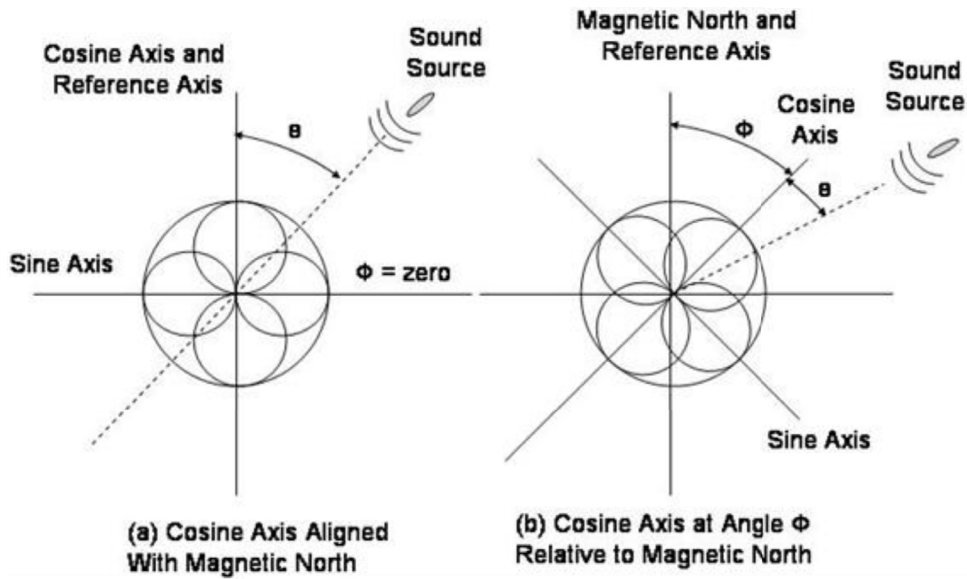


Fig. 12 – AN/SSQ-53 Hydrophone Directional Characteristics.

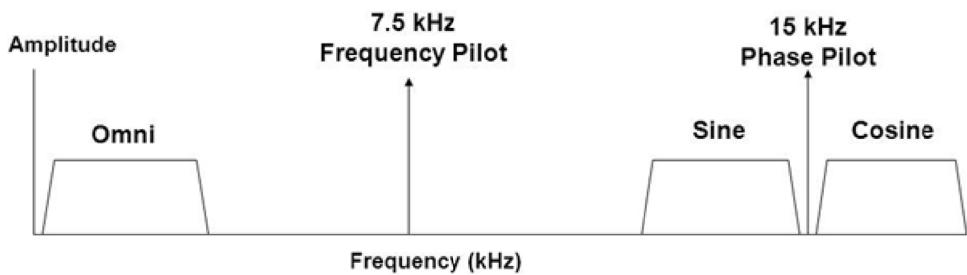


Fig 13 – Frequency Map of the DIFAR Multiplexed Data

The directional hydrophones that were used in DIFAR sonobuoys consisted of gradient devices which needed to be suspended from an electronics package containing the magnetic compass and maintain their orientation with respect to it. The hydrophone package was suspended below the electronics package by small compliant members. Because the directional gradient hydrophones were far more sensitive to movement than omnidirectional pressure hydrophones, it was important to isolate them from extraneous motion. To provide better attenuation of motion from the surface float, a damper disk or a damper bag entraining water was used between the compliant suspension and the lower unit. These devices used the water itself to provide mass-damping to the spring system, as well as isolation from the vibrations of cable strumming. The early DIFAR sonobuoy suspensions are illustrated in Fig. 14. Even after the DIFAR sonobuoy went into production in 1969, noise issues remained. The simple spring system of the suspension did not reduce sufficiently the disturbing vertical motion of the lower unit. Since the relative flow past the hydrophone was also of concern, drogues as well as mass-dampers were used just above the hydrophone to reduce this relative motion, as in Fig. 14.^{60, 61, 62}

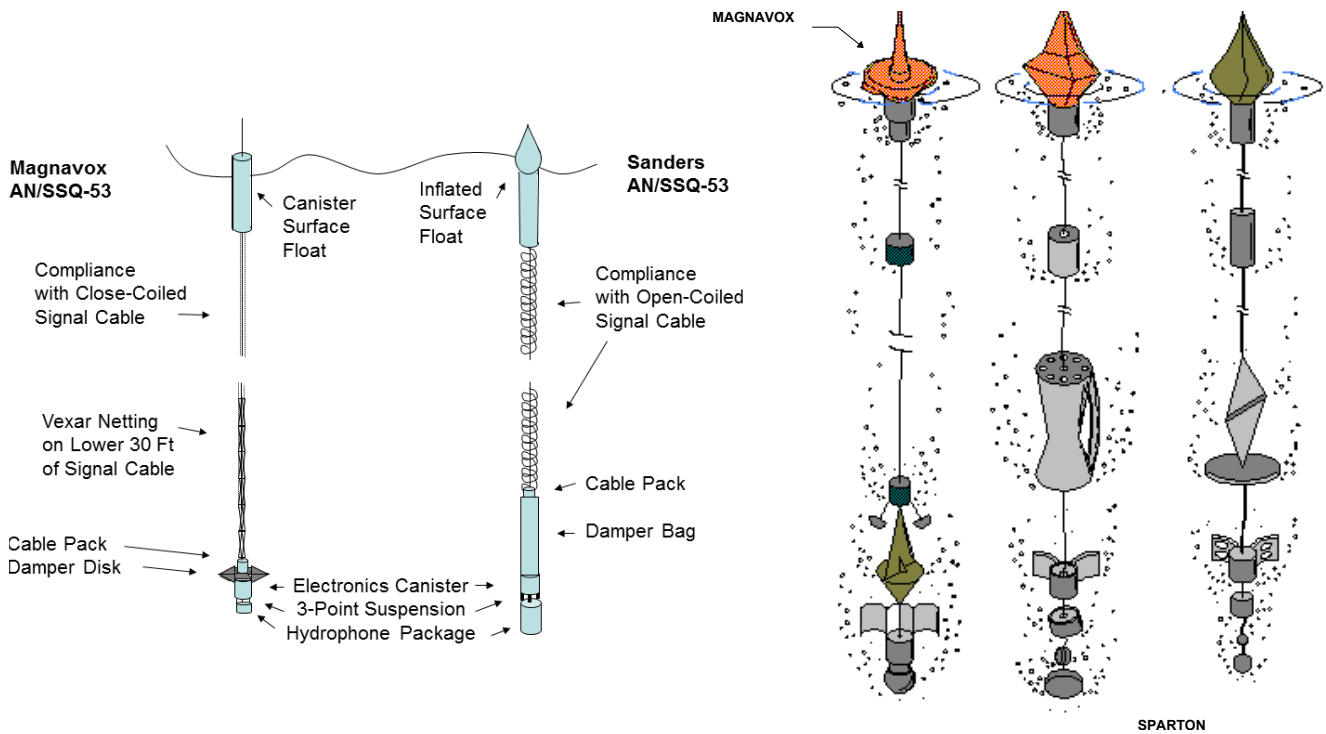


Fig. 14 – Early AN/SSQ-53 Suspensions (Left) and AN/SSQ-53A Production Designs (Right)

The Cold War of the 1970s and 1980s

In the late 1970s, Soviet Delta-class SSBNs replaced the Yankee-class on patrol through the GIUK gap. The U.S. Navy countered this threat by trailing the Soviet submarines with U.S. Attack Submarines and ASW Aircraft using passive sonobuoys for six 4-hour sorties per day to maintain 24-hour coverage.⁴⁵ For over two decades, the U.S.-U.S.S.R. submarine-antisubmarine competition was one-sided. The United States led the way in both submarine and ASW technology. The Soviet nuclear submarines were noisy, and the U.S. developed SOSUS and LOFAR and DIFAR sonobuoys to find and track them. Although the Soviets claimed that they had achieved parity with the United States in nuclear submarines in 1965 and had produced high-speed deep-diving (Alfa), long-range (Delta), and high-speed titanium-hulled (Papa) submarines in the early 1970s, the U.S. had a major acoustic advantage over the noisy Soviet submarines.³ The espionage by American naval personnel John Walker and Jerry Whitworth made the Soviet military aware of how noisy their submarines were, and the efforts to reduce the acoustic profile of the Victor III and Akula submarines can be traced to intelligence from the Walker spy ring.^{63, 64}

Submarines emit various underwater noises that can be detected and tracked by passive sonar. The sources of these noises include machinery vibration, flow over the submarine's hull, and propeller cavitation. Through dynamic balancing of rotating parts, the noise from shafts and interconnections can be reduced, and machinery noise can be reduced by mounting equipment in acoustically insulated boxes mounted on flexible supports to isolate them from the hull. Electronic active noise cancellation techniques also reduce machinery noise. The flow noise can be reduced by introducing air bubbles into the flow around the hull surface to interfere with and dampen the flow noise and interrupt the coupling of machinery noise at the interface between the hull and the water. The design of the propeller and the shape of the hull structure can affect propeller noise, and the onset of noisy cavitation can be delayed through the use of large-diameter, low-rpm propellers and through the introduction of high-pressure air bubbles through the rotating propeller blade or shaft. The radiation of machinery-induced noise can also be reduced by sound-absorbing anechoic coatings of composite materials applied to submarine hulls and interior decking. Anechoic tiles on submarine hulls not only reduce radiated noise but also absorb energy from active sonar to reduce the echo return. The coating material contained voids of various sizes to degrade the reflection of the sonar ping. The challenge in acoustic ASW entered a new phase in the mid-1970s with the quieter third generation Soviet nuclear subs, the Sierra, and Akula classes.^{63, 64, 65, 66}

Another quieting breakthrough for the Soviets came when the Japanese firm, Toshiba Machine Company, in collaboration with the Norwegian firm Kongsberg, illegally sold the Leningrad shipyard very large size multi-axis profiling machines to produce advanced quiet propellers. The combined results of these technologies generated a steep drop in the acoustic noise levels of the Soviet submarines.^{67, 68}

As the Soviet submarines grew quieter, it became harder and harder to detect them passively. One way to improve the detection range was to improve the signal-to-noise ratio. Sonobuoy self-noise had been reduced over the years, but the sensor was still subject to high ambient noise levels. Low frequency ambient noise came from distant shipping through convergence zone propagation. At the sensor, the shipping noise arrives from the horizontal. If the ambient noise level could be attenuated, a higher signal-to-noise ratio for the submarine acoustic emissions could be achieved by maximizing acoustic reception at arrival angles suitable to submarine detection.⁵⁹

The AN/SSQ-77 Vertical Line Array DIFAR (VLAD) sonobuoy development was initiated in the late 1970s to accomplish this enhanced signal-to-noise capability. The buoy had the directional capability of a DIFAR hydrophone centrally located in a vertical line array of omnidirectional hydrophones to provide 10 to 15 dB of array gain. The array was shaded to form beams and reduce sensitivity in the horizontal direction. VLAD was produced as the AN/SSQ-77A in 1981 and improved in the AN/SSQ-77B with additional hydrophones, selectable depths, and selectable beam patterns with different arrival angles.^{69, 70} Figure 15 shows configurations of the AN/SSQ-77B suspensions.

With the decrease of detection ranges for passive sonobuoys, more emphasis was placed on localization with active sonar. The B-size AN/SSQ-15 was replaced in the late 1960s by the lighter A-size AN/SSQ-47 range-only active sonobuoy, which produced a free-running continuous wave pulse every ten seconds at one of six fixed sonar frequencies in the 13 kHz to 19 kHz band.^{43, 69, 71}

In the early 1970s, the AN/SSQ-50 Command Activated Sonobuoy System (CASS) was introduced to replace the AN/SSQ-47. This was also a range-only A-size sensor, but it was not continuously pinging, but pinged when commanded through a UHF radio link with the aircraft. The transducer initially deployed to a depth of 60 feet and could be commanded to deploy to the deeper depth of 1,500 feet. The 38-pound CASS was available in four fixed sonar frequencies in the 6.5 kHz to 9.5 kHz band. Each frequency had different transducer requirements, so the transducers were not interchangeable. The four flavor buoys operated on specific fixed channels within the 31 sonobuoy RF channels.⁶⁹

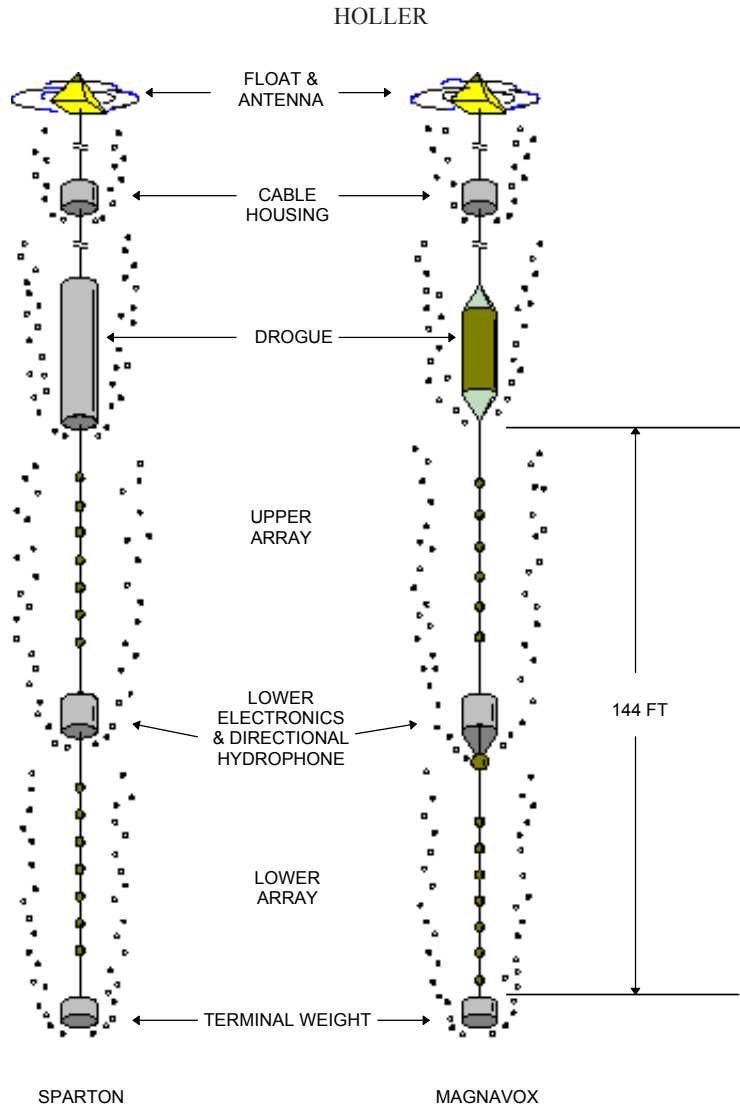


Fig. 15 – The AN/SSQ-77B VLAD Sonobuoy

In the late 1970s, the AN/SSQ-62 Directional Command Activated Sonobuoy System (DICASS) was introduced. Similar to the CASS in size, weight, and sonar frequency, the DICASS provided directional capability and added FM sweeps to the CW sonar. Although the early DICASS buoys had the same transducer problem as the CASS buoys, later versions had transducers that could accommodate all four selectable acoustic frequencies. With selectable 99 RF channels, all DICASS sonobuoys are acoustically identical.⁶⁹ Figure 16 shows an artist's conception of the deployed CASS and DICASS. The bridle and fins on the deep unit were to provide verticality to the transducer in ocean current flow and stable descent when the unit was commanded to deeper depths.

The AN/SSQ-101 ADAR (Advanced Deployable Acoustic Receiver) sonobuoy was developed as the receiver for an active source in the early 1990s by ERAPSCO, a joint venture by Magnavox (now USSI) and Sparton. ADAR, shown in Fig. 17, was a selectable frequency band A-size sonobuoy with a 40-element, 5-arm planar array with real-time beamforming. The fall of the Berlin Wall in 1989 and the collapse of the Soviet Union in 1991 signaled the end of the Cold War, but ASW sonobuoys continue to be developed to counter the proliferating threat of quiet submarines throughout the world.

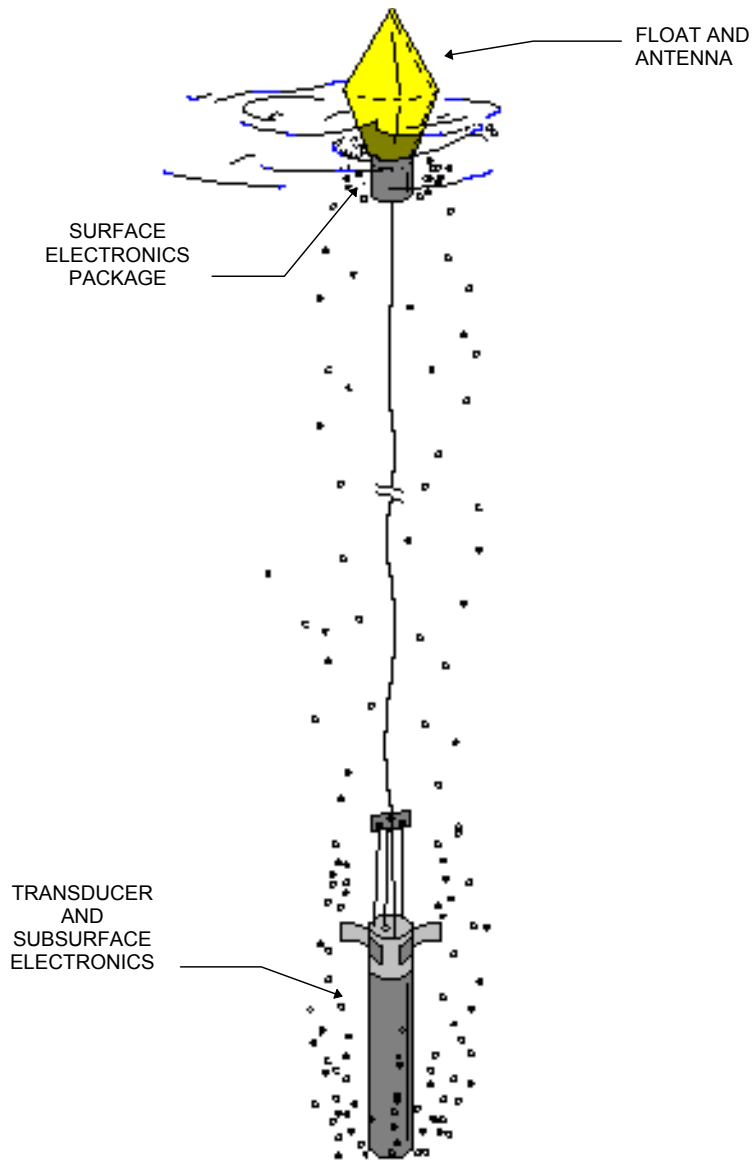


Fig. 16 – AN/SSQ-50 and AN/SSQ-62 In-Water Deployment

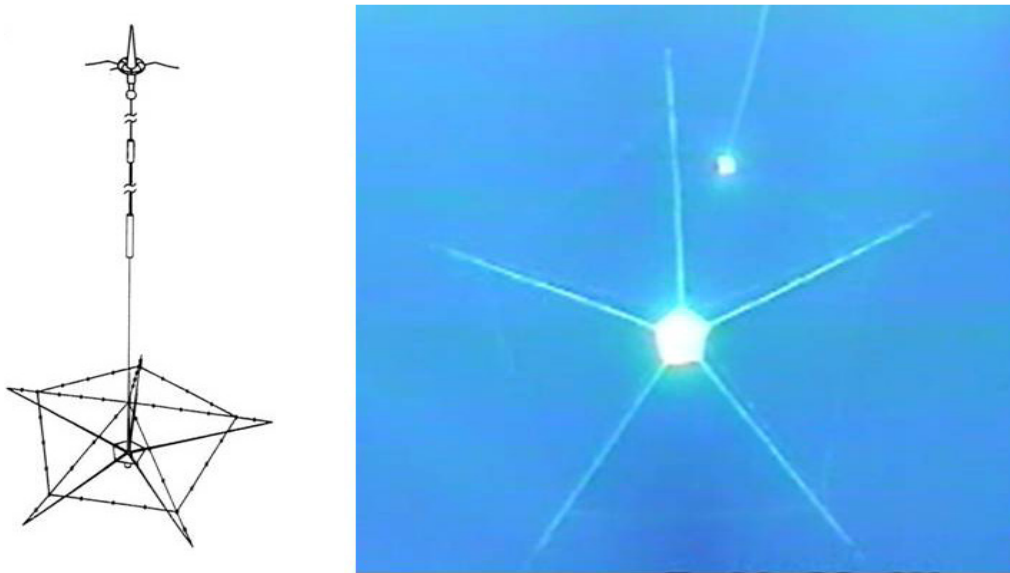


Fig. 17 – Conceptual Drawing of the ADAR Array (left) and the Deployed Array (right)

IV. SUMMARY

The ASW sonobuoy was an innovation motivated by the need to combat the German submarine threat during World War II. It was made possible by the advances in underwater acoustics, transducer materials, and electronics and made practicable by the inventiveness and dedication of the scientists and engineers. The age of aviation was coming into its own, and the airplane became the ASW platform that could span vast areas of the ocean quickly in pursuit of submarines. The sonobuoy became the underwater ears of air ASW. As submarines became more technologically advanced, achieving faster speeds, deeper depth, longer ranges, and quieter emissions, sonobuoys evolved to keep pace. The sonobuoy was initially a passive sensor, divided into two branches, omnidirectional and directional sonobuoys. The simpler omnidirectional sonobuoys set the standard in size and ease of use, in spite of their ambiguity in determining submarine location. Pairs of buoys were dropped to overcome this problem using CODAR. Broadband gave way to narrowband and LOFAR, and passive omnidirectional buoys were employed with explosive sources as Julie came into use. Directional buoys lagged in development until orthogonal directional sensors made possible the A-size DIFAR. After that, the omnidirectional buoys took a back seat. Improvements included the Vertical Line Array DIFAR, and the calibrated omnidirectional AN/SSQ-57 was merged with DIFAR in the AN/SSQ-53F. Toward the end of the Cold War, the quiet threat led to a more sophisticated method of echo ranging and multistatic active sonar with the AN/SSQ-101 ADAR sonobuoys as the receiver.

Meanwhile, active sonobuoys, had begun to be developed with the B-size AN/SSQ-15. As an alternative to explosive sources, the active sonobuoy used coherent continuous wave sound and was both source and receiver. Once the sound frequency was reduced, the active buoy could be made in A-size, and the AN/SSQ-47 and AN/SSQ-50 CASS became the active equivalents of the omnidirectional passive buoys. Directional capability led to the DICASS (AN/SSQ-62) sonobuoy.

Although other sensors, such as Magnetic Anomaly Detection (MAD), Periscope Detection Radar (PDR), Light Detection and Ranging (LIDAR), wake detection, and helicopter dipped sonar, have been included in the air ASW arsenal over the years, the ASW sonobuoy has continued to provide the most consistent and reliable means to search for and localize submarines from the air.

V. ACKNOWLEDGEMENT

The author wishes to acknowledge the Office of Naval Research, who sponsored the *The Ears of Air ASW – A History of U.S. Navy Sonobuoys*¹ from which a large part of this article is excerpted.

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